Ch. 3 Introduction to Optical Fibre

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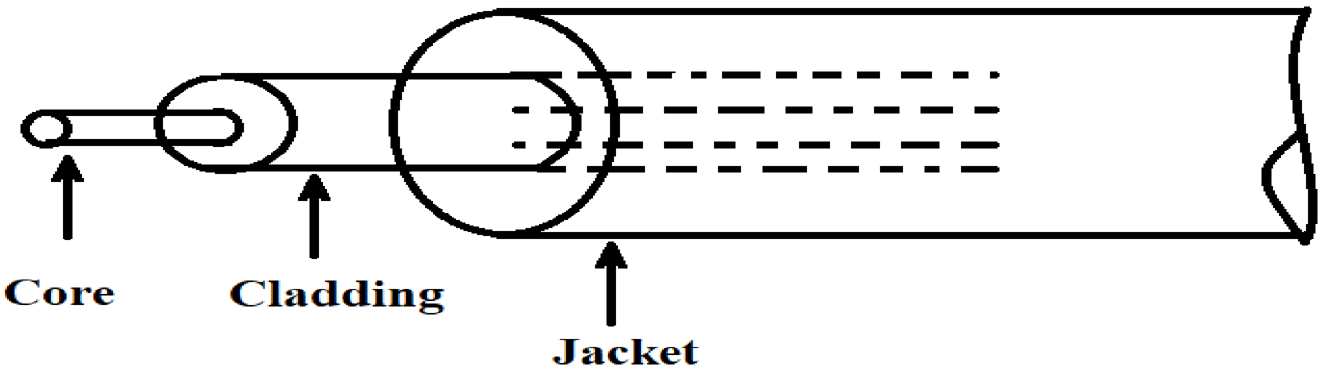
Introduction:

- A thin flexible and transparent glass fibres (wire) prepared for light propagation is called optical fibres.
- Optical fibres are the light equivalent of microwave waveguides with additional advantage of a very wide bandwidth.
- Physically an optical fibre is very thin and flexible medium, having a cylindrical shape consists of three sections; i) the core, ii) the cladding and iii) the jacket.



- The innermost section is core and is made of glass or plastic having high refractive index.

- This is the actual fibre and has the remarkable property of conducting an optical beam. It acts as a guide for light.
- Core is surrounded by its own cladding, a glass or plastic coating, that has optical properties which are very different from those of core. Its refractive index is less than that of core.
- The outer section is called jacket or sheath made of plastic or polymer and other materials and is provided for protection against moisture, absorption, crushing and other environmental dangerous.
- The core acts like a continuous layer of two parallel mirrors. A signal is first encoded into a light beam which is then passed in between the two boundaries and propagated as a result of multiple internal reflections.

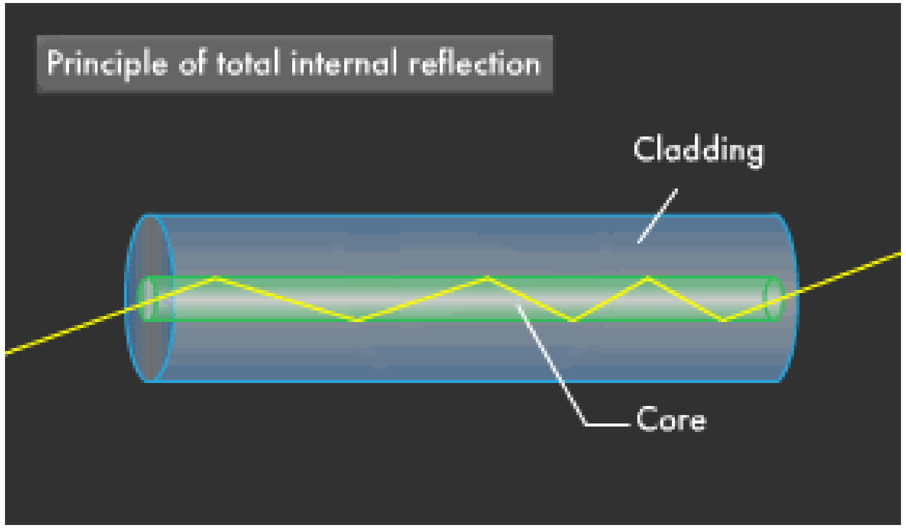
Importance of Optical Fibres:

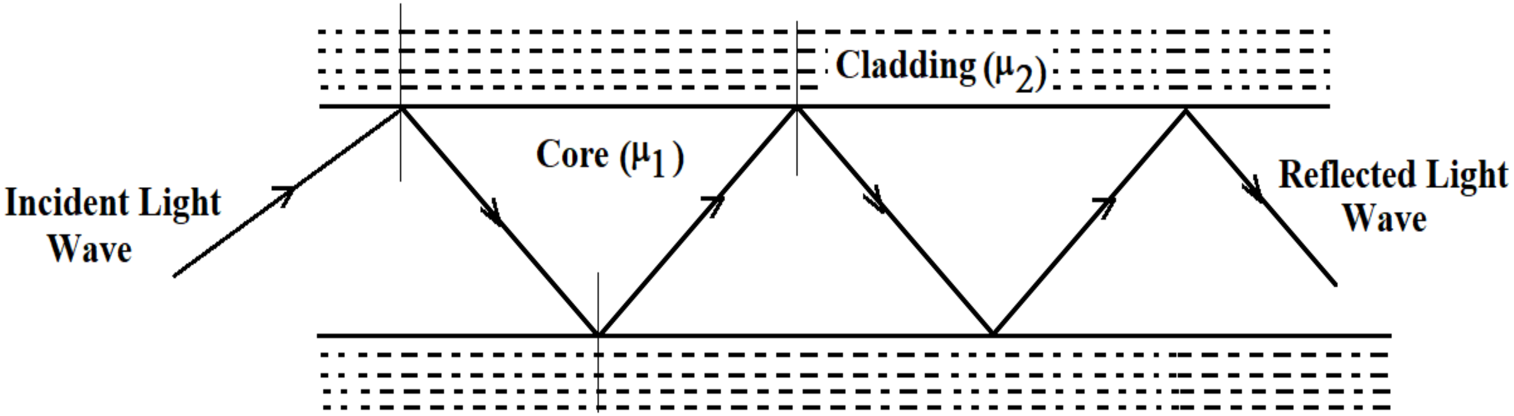
The following are the main advantages of optical system:

- Attenuation in a fibre is obviously lower than that of coaxial cable or twisted pair and is constant over a very wide range. So, transmission within a wide range of distance is possible without repeaters etc.
- Smaller size and lighter weight: Optical fibres are considerably thinner than coaxial cable or bundled twisted pair. So, they occupy much less space.
- Electromagnetic isolation: Electromagnetic waves generated from electrical disturbances or electrical noises do not interfere with light signals. As a result, the system is protected from interference, impulse noise or crosstalk.
- No physical electrical connection is required between the sender and the receiver.
- The fibre is much more reliable because it can better with stand environmental conditions such as pollution, radiation and salt produce no corrosion. Its life is longer in comparison to copper wire.

- Almost there is no crosstalk in optical fibre and hence transmission is more secure and private as it is very difficult to tap into fibre
- Greater bandwidth: The bandwidth of optical fibre is higher than that of an equivalent wire transmission line.
- As fibres are very good dielectrics, isolation coating is not required.
- Data is much higher in a fibre and hence much more information can be carried by each fibre then by equivalent copper cables.
- The cost per channel is lower than that of an equivalent to wire cable system.
- Due to non-inductive and non-conductive nature of fibre there is no radiation and interference on other circuits and Systems
- Greater repeater spacing
- The raw material is available in plenty.

Propagation of light through Optical Fibre: -





If light enters wave at one end of a fibre, most of light is propagated the length of the fibre and comes out from the other end. This propagation of light inside a fibre is due to the total internal reflection of light waves.

The total internal reflection in the walls of the fibre can occur if and only if the following conditions are satisfied:

i) the core has higher refractive index μ_1 than the cladding μ_2 i.e., $\mu_1 > \mu_2$, light travels from denser medium to rarer medium.

ii). the light should be incident at an angle which is greater than the critical angle.

[The critical angle is the angle of incidence, for which the angle of refraction is 90°].

- So far making of glass fibre core has higher refractive index than cladding.
- Light wave which travels along the core and meets the cladding at the critical angle of incidence will be totally reflected.
- This reflected ray will then meet the opposite surface of the cladding again at critical angle and so it is again totally reflected.
- Therefore, light wave is propagated along the fibre core by series of total internal reflections from the core cladding interface.

Acceptance angle and acceptance cone of a fibre:

- We know that light wave travels along the core and meets the cladding at the critical angle of incidence θ_c, will be totally reflected.
- This reflected ray will then meet the opposite surface of the cladding, again at the critical angle θ_c and so it will again totally reflected.
- Any other light wave, which is meeting the core cladding interface at or above the critical value θ_c, will also be totally reflected and hence will propagate along the core.
- However, any light wave meeting the core cladding interface at an angle below θ_c will pass into and be absorbed by the cladding.
- For a fibre for which refractive index of core is greater than cladding, light impinging on the core within a critical angle θ_c is coupled into the fibre and will propagate.
- If the external incident angle is θ_0 corresponding to the critical angle of incidence θ_c at the core cladding interface of the fibre, the light will stay in the fibre.

- The any light wave impinging on the core within the external incident angle θ_0 is coupled into the fibre and will propagate. This angle is called the acceptance angle.
- It is unique for a particular fibre but different for different fibres and depends on the material and core diameter.

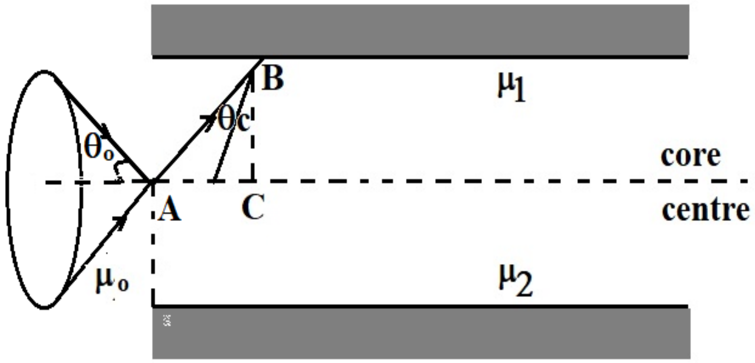


Fig. (a)

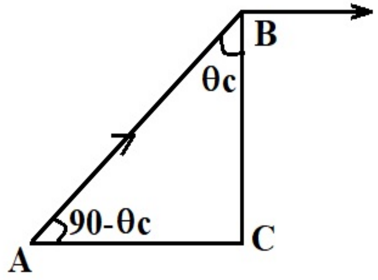


Fig. (b)

- From figure (a) and (b), by applying law of refraction at A and B we get
  - $\mu_0 sin\theta_0 = \mu_1 \sin(90 - \theta_c) \quad ------(1)$
  - $\mu_1 sin\theta_c = \mu_2 sin90^o \; --------(2)$
  - $\mu_1 sin\theta_c = \mu_2$
  - $sin\theta_c = \frac{\mu_2}{\mu_1}$

From equation (1),

$$\mu_0 sin\theta_0 = \mu_1 cos\theta_c = \mu_1\sqrt{1 - sin^2\theta_c}$$

$$\mu_0 sin\theta_0 = \mu_1\sqrt{1 - \left(\frac{\mu_2}{\mu_1}\right)^2} = \sqrt{\mu_1^2 - \mu_2^2}$$

$$sin\theta_o = \frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_0}$$

$$\therefore Half\ acceptance\ angle\ \theta_0$$

$$= sin^{-1}\left(\frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_0}\right)$$

If the fibre surrounding medium is air i.e. $\mu_0 = 1$

$$\therefore Half\ acceptance\ angle$$

$$\theta_0 = sin^{-1}\left(\sqrt{\mu_1^2 - \mu_2^2}\right)$$

Thus, the light which travels within a cone defined by the acceptance angle is trapped and guided.

This is the fundamental property of light propagation in a fibre. This cone is referred as acceptance cone.

Numerical Aperture:

- The numerical aperture of the optical fibre is also called the figure of merit for optical fibres.
- The numerical aperture of an optical fibre is a dimension less number that characterizes the range of angles over which the system can accept or emit light.

Therefore, Numerical aperture of an optical fibre defined as,

$$NA = sin\theta_0(max) = \frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_0}$$

If the fibre is surrounded by air (μ_0=1) then,

$$NA = \sqrt{\mu_1^2 - \mu_2^2}$$

$$NA = \sqrt{(\mu_1 + \mu_2)(\mu_1 - \mu_2)}$$

Generally, μ_1 is only a few percentage greater than μ_2 i.e. $\mu_1 \approx \mu_2$

$$NA = \sqrt{2\mu_1(\mu_1 - \mu_2)} = \sqrt{2{\mu_1}^2 \frac{(\mu_1 - \mu_2)}{\mu_1}}$$

$$= \mu_1\sqrt{2\Delta}$$

Where $\mu_1+\mu_2= 2\mu_1$ and $\Delta= \frac{\mu_1-\mu_2}{\mu_1}$

Δ is a fractional difference between the refractive indices of the core and cladding.

It has been observed that numerical aperture for the fibres used in short distance communication are in the range of 0.4 to 0.5, whereas for long distance communications numerical apertures are in the range 0.1 to 0.3.

Example: 1) Compute the NA and acceptance angle of an optical fibre in which core have refractive index 1.55 and for cladding 1.50.

Solution: Given

$$\mu_1 = 1.55 \text{ and } \mu_2 = 1.50$$

Numerical aperture of optical fibre is,

$$NA = \sqrt{\mu_1^2 - \mu_2^2}$$

$$NA = \sqrt{(1.55)^2 - (1.50)^2}$$

$$NA = \sqrt{2.4025 - 2.25}$$

$$= \sqrt{0.1525} = 0.3905$$

Acceptance angle is,

$$\theta_0 = sin^{-1}(NA)$$

$$= sin^{-1}(0.3905) = 23^o$$

2. A fibre has a refractive index of its core 1.46 and cladding 1.45. compute the numerical aperture, acceptance angle and the fractional difference in the refractive index.

Solution: Given

μ_1 = 1.46 and μ_2= 1.45

Numerical aperture of optical fibre is,

$$NA = \sqrt{\mu_1^2 - \mu_2^2}$$

$$NA = \sqrt{(1.46)^2 - (1.45)^2}$$

$$NA = \sqrt{2.1316 - 2.1025} = \sqrt{0.0291}$$

$$= 0.1706$$

Acceptance angle is,

$$\theta_0 = sin^{-1}(NA) = sin^{-1}(0.1706) = 9^o 49'$$

Fractional difference in Refractive index is

$$\Delta = \frac{\mu_1 - \mu_2}{\mu_1}$$

$$\Delta = \frac{1.46 - 1.45}{1.46} = \frac{0.01}{1.46} = 0.00685$$

$$= 6.85 \times 10^{-3}$$

3. Classification of Optical Fibre:

The optical fibres are mainly classified into three groups:

i) Stepped index multimode fibre

ii) Graded index multimode fibre

iii) Single mode fibre

i) Stepped index fibre:

If the refractive index of the cladding changes abruptly from μ_1 to μ_2 then the fibre is called stepped index fibre.

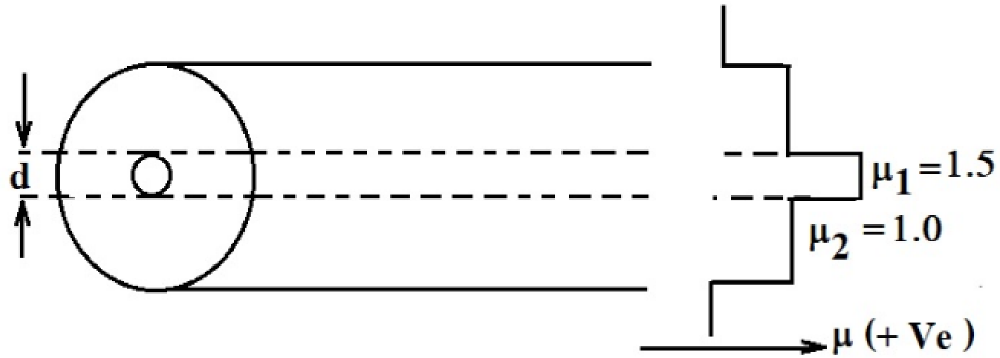


Fig. (a) Basic Structure

The basic structure of step index fibre is shown in Fig.(a).

It has two portions like two concentric cylinders.

The inner cylinder is called the core. The outer cylinder may be made of the air i.e., core is open to air.

The difference between core and cladding refractive index is large. As a result the acceptance angle will be large.

But as the fibre core is open, the fibre as a whole will be mechanically weak. To overcome this, we should use a fibre of core diameter more than 200 μm.

The second type of this class of fibre uses plastic as its cladding.

This gives higher losses.

However, it is less expensive than the others. Its refractive index profile is as shown in Fig. (b).

The third type of this class of fibre uses glass cladding, but with refractive index μ_2 slightly lower than that of the core glass.

This type of stepped index fibre is very commonly used because it can be fabricated with small core diameters, with greater mechanical strength.

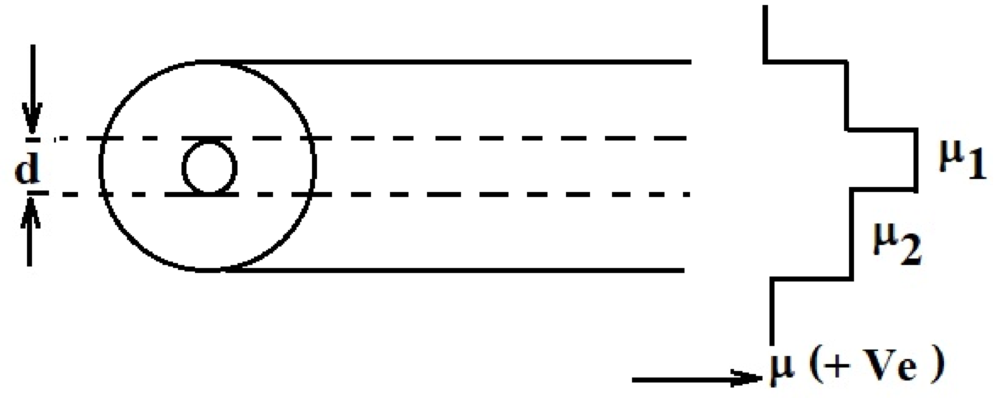


Fig. (b)

As the difference in the two refractive indices is very small, hence the single mode propagation becomes possible.

Outside the cladding, there is a primary coating and a buffer jacket, composed of polymer which protect the light guide from scratches etc. and thus enhances its tensile strength.

In a stepped index fibre light propagates in different modes, each with a different path and transit time. If the diameter of the core satisfies the condition

$$d > \frac{0.766\lambda}{NA}$$

Where λ is operating wavelength and NA is numerical aperture.

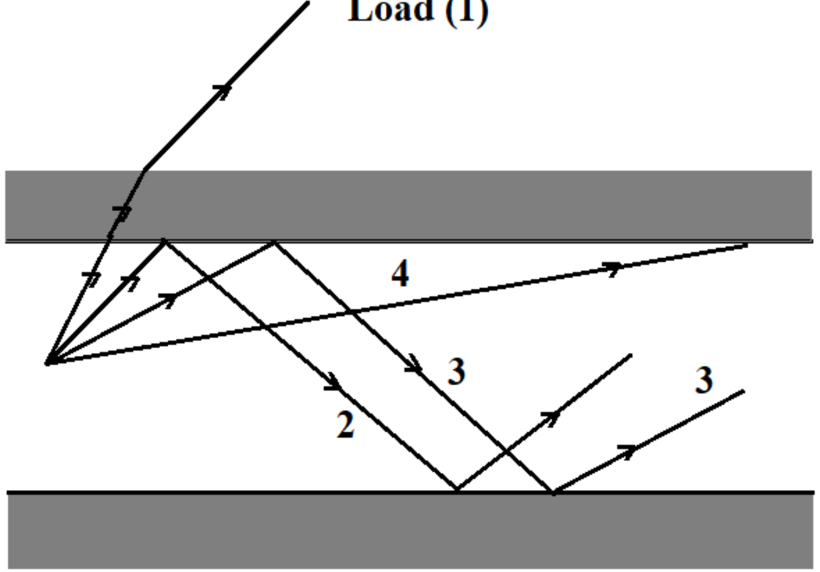


Fig. (c)

A number of modes existing through the light pipe become possible. Then the angle with respect to the core exit will different as shown in Fig. (c), where the numbers 1, 2, 3, 4 represent different modes.

The optical power of an input optical pulse is a distributed uniformly among these modes, provided the light from the emitter is uniformly distributed over the acceptance cone. If the number of modes in stepped index fibre is larger than 50, then the number of modes in step index fibre is given by

$$N = \frac{2\pi^2 a^2 (NA)^2}{\lambda^2}$$

Where a-is radius of core.

Stepped index monomode fibre:

- The various light waves travelling along the core will have propagation paths of different lengths. Hence, they will take different times to reach a given destination.
- Thus, a distortion is produced and is called the transit time dispersion. This dispersion sets an upper limit on the rate at which light can be modulated by an analog or digital electrical signal.
- As a result of this distortion, the variation of successive pulses of light overlaps into each other and there by cause of distortion of the information being carried.
- However, this defect can be minimised by making the core diameter of the same order as the wavelength of light wave to be propagated. The resultant propagation is a single light wave. This type of fibre is called as stepped index monomode fibre.
- The transit time dispersion problems can be solved by making the core very thin, so that the diameter of the core is of the same order as the wavelength of the light wave to be propagated as shown in Fig. (a). This type of fibre is referred as a stepped index monomode fibre.

The chief characteristics of stepped index fibre are as follows:

i) small core diameter,

ii) low numerical aperture,

iii) Low attenuation,

iv) very high bandwidth

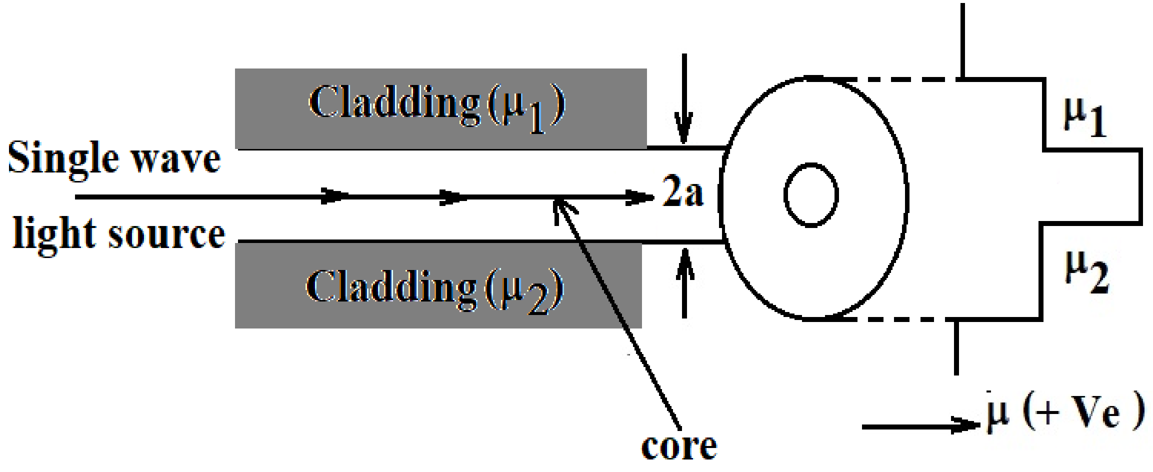


Fig. (a) Monomode Fibre

In order to get single mode, with all other modes cut-off, the diameter of the core must satisfy the relation,

$$d < \frac{0.766\lambda}{NA}$$

Hence if the operating wavelength is 1.3μm, the core diameters are in the range of 6 to 10 μm. The term mode field diameter (2Fd) as shown in Fig. (b) is another important parameter for a single mode fibre.

- It shows the light guiding property of fibre, by indicating the boundary where the electric field of optical wave falls to 1/e th (i.e. 36.8%) of that at the core centre.
- In single mode fibre, a significant amount of the power residues outside the fibre core.
- The distribution of the optical electric field with the radial position across the core as shown in Fig. (b) can be described by Gaussian expression near the cut-off wavelength as follows:
- $E(x) = E_0 e^{-\left(x/F_d\right)^2}$
- Where $F_d = \frac{1}{2} \times mode\ field\ diameter$

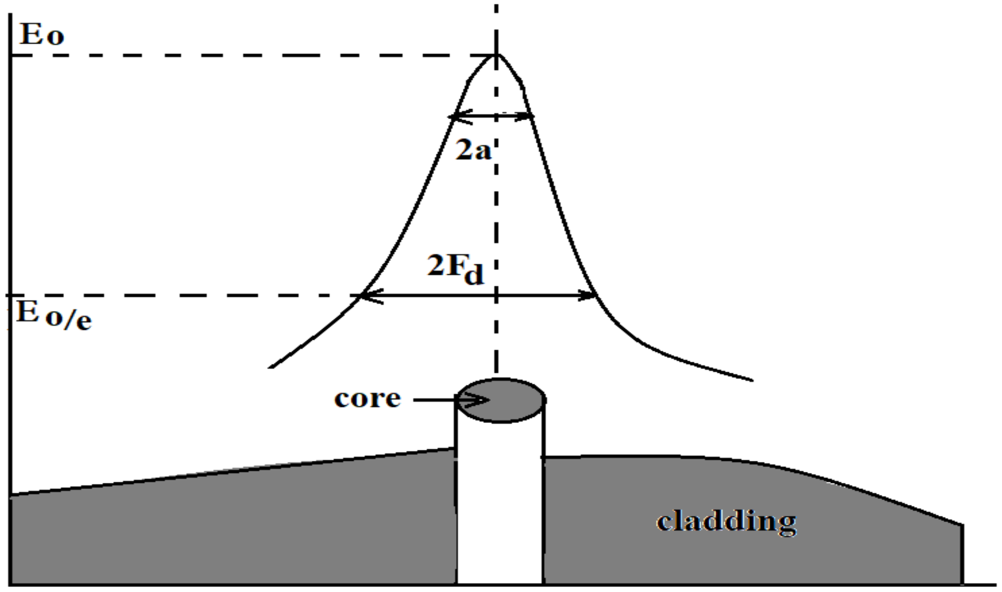


Fig (b) Optical power distribution across the cone of the step index single mode fibre

Greater the ratio (F_d/a), the larger amount of light that propagates in the cladding.

In the structure of stepped index monomode fibre, the cladding is kept very thick so that residual field at the cladding outer diameter is very insignificant, which is present at outer boundary of the cladding is radiated.

The theoretical value of $2F_d$ is

$$2F_d = 2a[0.65 + 0.434\left({}^{\lambda}/_{\lambda_c}\right)^{3/2} + 0.0149\left({}^{\lambda}/_{\lambda_c}\right)^{6}$$

Where λ- is operating wavelength, λ_c – cut off wavelength and *2a*- core diameter.

This shows that for a particular cut-off wavelength the F_d increases with operating wavelength.

Disadvantages of Monomode fibre:

Monomode fibre optical cable is more suitable for long runs application when compared with multimode fibre cable.

The Monomode fibres have following disadvantages:

i) The use of very thin cores creates mechanical difficulties in the manufacture, handling and splicing the fibre.

ii) This type of fibre is very expensive to deploy and operate since laser-based equipment generate more heat.

iii) The lasers required are costly and can be used with only one cable at a time.

iv) The dependency on lasers means that single-mode cables are less versatile and more limited in their applications.

This type of fibre is used the undersea cables where the expense is justified by high return of earned income.

Plastic fibres

- Plastic fibre (plastic core) have been manufactured from a polymer perform drawing into a fibre.
- The Losses associated with these fibres are usually in the hundreds of decibels.
- They operate at a low temperature. We can use plastic fibres up to a maximum of 125°C, while glass fibres can be used right up to a maximum temperature of 1000°C.
- However, plastic fibre and cables have an inherent potential for many present and future applications.
- It is an ideal medium for sensors, process control and short distance communications.

The characteristics of latest type of plastic fibres are as:

- high light gathering capacity
- large core area
- low-cost components- fibre cables, data links, LEDs.
- Uses of visible LEDs which makes testing very easy-if you see light, LED is ON.

- Easy to connectorized, cleave and crimp connectors perfect for assembly line for field installation.
- By some technological breakthrough plastic fibres have been fabricated with the loss approx. 88 dB/Km.
- The wavelength of operation for these fibres is in the range of 1.3 μm to 1.4 μm.
- Plastic fibres are not available for use at long wavelength, because, fibres of that type are very difficult to fabricate and also very expensive.
- A fibre having glass core and plastic cladding is called as plastic clad silica or PCS fibre.

The characteristics of such fibres are as follows:

i) It has a high numerical aperture.

ii) Large core diameter

iii) high attenuation

iv) low bandwidth.

- The advantage of laser core is the greater coupled power.
- The high value of NA permits the use of less expensive surface emitting LEDs.
- Other than high attenuation and low bandwidth,
- there are some major problems with the plastic fibres.
- Plastic fibres have very poor mechanical strength.
- They have low maximum operating temperature.

Latest Developed Types of Optical Fibre:

1) High purity silica fibre (HPSUV):

- This type of fibre is a suitable for transmission of light in the range 180 to 800 nm.
- It is good as well as cheap. It is sometimes coated with aluminium which gives very high mechanical strength and extra power handling capability, as aluminium dissipates heat more quickly.
- The aluminium coated fibre allows use up to 400°C and in vacuum also.

The main characteristics of HPSUV fibres are as follows:

- It is type of step index multimode fibre.
- The core material is high purity synthetic silica.
- The cladding material is doped silica.
- Primary coating is a aluminium (μPSUVA) or polymer.

- Optical secondary coating is polymer.
- Numerical aperture is 0.24
- Tensile strength is about 7 GPa (HPSUVA)
- Minimum bend radius is 40 times fibre radius.
- Operating temperature range is -169 to 400°C
- Humidity 100%
- Radiation resistance is good.
- Mechanical intensity of the transmitted power is
  - for CW up to 100 Kw/cm^2
  - pulse up to 500 Kw/cm^2
- Guaranteed spot values of attenuation is
  - 248 nm (Kr laser) ∠1.2 dB/m
  - 3058 nm (XeCl laser) ∠0.26 dB/m

2) High purity silica (HPSIR)

- HPSIR type of fibre is similar to the HPSUV fibre with a slightly different dopants to give it a longer wavelength capability in the near IR from 500 nm to 2600nm.
- The same comments concerning strength and power handling apply.

3) Halide

This type of fibre is suitable for transmission of light from 3 to 15μm.

They have low losses and are currently known optical fibres for transmission of light from high power, long length laser like the CO_2 laser.

They are very flexible and much more convenient than normal mechanical delivery systems for those long wavelengths.

These fibres comprise a core polycrystalline silver halide, surrounded by an opaque tube; because of the high refractive index (2.2) of the material, the total internal reflection takes place at the boundary with air.

The tube is necessary to present UV light from reaching the core, which causes premature failure.

The normal lifetime of these fibres is 6 to 12 months depending on how they are used.

The characteristics of halide fibres are as follows:

i) Numerical aperture is less than 0.7.

ii) the outer diameter with the protective coating is 0.36 to 1.5mm.

iii) core diameter is about 0.1 to 1.2mm.

iv) attenuation at 10.6μm CO_2 laser 0.5 to 1.5 dB/m.

v) activation at 5 to 6μm CO2 laser is less than 2 dB/m.

vi) usable wavelength range is 3 to 15mm.

vii) maximum length is less than 15m

viii) yield strength is 150 to 170 Mpa.

ix) Radius of Elastic bending is greater than 0.4cm.

x) Operating maximum temperature is greater than 100°C.

Tapered Optical Fibre:

- Tapered fibres are useful for getting the maximum amount of power from a poor-quality laser spot, into a fibre.
- The use of tapered optical fibre is an efficient low-cost method of transforming a poor-quality laser beam into uniform output spot.

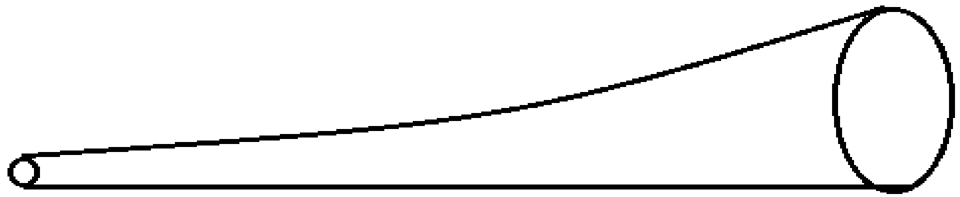


Fig (a) Tapered Fibre

The concept of conservation of brightness states that the spatial and angular parameters of light, anywhere within or at the either end of the taper are mutually connected by formula

$$A_i \mu_i^2 sin^2\theta_i = A_0 \mu_0^2 sin^2\theta_0$$

Where μ_i and μ_o represents refractive indices and θ_i and θ_o angles.

Subscripts ‘i’ and ‘o’ refers to input and output.

$$\therefore \frac{A_i}{A_o} = R^2$$

Where R tapered ratio and it follows that $\frac{(NA)_i}{(NA)_o} = R$

- It should be noted that if the product of the input NA and taper diameter ratio R exceeds the NA of tapers pigtail, the light will escape into the cladding and will be lost.
- In that case the above relation is no longer true.
- To avoid light losses, the NA of light beam at the tapers input should be less than the particular value NA(taper)/R.

The chief characteristics of tapered fibres are as follows:

- the input and output ratio is up to 5:1.
- input core diameter is 100µm to 4.0mm.
- output core diameter is 50µm to 1.5mm.

- taper length is 1-3m
- total length is typical 3 to 10m.
- core material is pure synthetic silica.
- primary coating is aluminium or acrylate.
- optical secondary coating with epoxy acrylate fluoropolymers.
- operating temperature is 196 -400°C.
- humidity 100%
- radiation resistance is good
- power transmission is
  - for CE up to 100 Kw/cm2.
  - Pulsed 145, 500 Kw/cm2.
- NA is 0.24.

Thank You!